

---

# **Springer Praxis Books**

Astronautical Engineering

More information about this series at <http://www.springer.com/series/5495>

---

Barrie D. Dunn

# Materials and Processes

for Spacecraft and High Reliability  
Applications

Barrie D. Dunn  
School of Engineering  
University of Portsmouth  
Portsmouth  
UK

Published in association with Praxis Publishing, Chichester, UK

ISSN 2365-9599                      ISSN 2365-9602 (electronic)  
Springer Praxis Books  
ISBN 978-3-319-23361-1              ISBN 978-3-319-23362-8 (eBook)  
DOI 10.1007/978-3-319-23362-8

Library of Congress Control Number: 2015948763

Springer Cham Heidelberg New York Dordrecht London  
© Springer International Publishing Switzerland 2016

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made.

Cover design: Jim Wilkie

Cover images: Front cover top—The Falcon 9 rocket streaks towards space from Florida's Cape Canaveral Air Force Station containing supplies, including the first 3D printer in space and a troop of 20 mice, for the International Space Station (*Courtesy* SpaceX). Front cover lower—the assembly and integration of a satellite in SSTL's clean-room (*Courtesy* of Surrey Satellite Technology Ltd.). Rear cover—Vega VV05 in its mobile gantry prior to launch at Europe's Spaceport in Kourou, French Guiana (*Courtesy* ESA-M. Pedoussaut).

Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media  
(www.springer.com)

*Talking of education, 'People have now a-days, (said he,) got a strange opinion that everything should be taught by lectures. Now, I cannot see that lectures can do so much good as reading the books from which the lectures are taken. I know nothing that can be best taught by lectures, except where experiments are to be shewn. You may teach chemistry by lectures—You might teach making of shoes by lectures!'*

Samuel Johnson, 1766  
(from Boswell's *Life*)

*This book is dedicated to Cato and Dennis*

---

## Preface

This book, as implied by the title page, is an extensively revised version of the former “*Metallurgical Assessment of Spacecraft Parts, Materials and Processes*” published in 1997. The present title has been modified to set it apart from the previous work and describe its expanded content. The book has become more voluminous, this reflects the huge advances made during the past 20 years when we have witnessed the increased usage of modern materials and manufacturing techniques that were unforeseeable when the former book was written. Also, the number of case studies and amount of general information has been extended to become a source for engineers, space scientists, laboratory experimenters and technicians. Although much of the book considers metallurgical aspects of spacecraft engineering, there is now basic advice covering organic and ceramic materials as well as techniques available for assembling them into essential sub-systems, reliable parts and structures.

A good number of the original illustrations are retained but many new ones have been added. Several images reflect the quite remarkable outcomes of space projects. These include high resolution images of Earth taken by satellites which are relevant for surveillance and the forecasting of weather. Also included are fly-by images of enigmatic little moons and comets captured by spacecraft after many years of voyaging in search of life and the origins of water in our own Solar System. Equipment on-board the International Space Station and satellite-based communications are mentioned. These have all been made possible by breakthroughs in materials, processes and electronic-engineering.

Plato saw engineers as “doers” not “thinkers”. From ancient times no one expected engineers to question what they were asked to build and consider the consequences of such achievements. Nowadays engineers are more confident in their social role and have learned to say “no” when the products are questionable or environmental damage may occur—the generation of space debris is one pertinent example. Hopefully, some “lessons learnt” guidance may ensue from the case studies and failure analyses recorded in this book. In 1986 engineers said “go” to the Challenger launch—other engineers said “no” but were over-ruled and the space shuttle exploded shortly after lift-off. It is only in hindsight that we understand that decision making can be extremely difficult, but such decisions must consider input from all engineering disciplines and the recognition of material properties is vital.

A casual review of the Contents and Index will suggest to the reader that the subject matter is likely to be of interest not only to spacecraft engineers, but in the broader sense, to workers in quite different areas where metals, organic materials, composites, ceramics and glass are used under terrestrial conditions or within high vacuum systems. Advancements in technology always produce questions related to the reliability of new systems. Materials testing to agreed codes of practice have been shown to help maximise the reliability of new materials, processes, and applications. Metallography (or “materialography”) has led to an increased understanding of failure modes. Much emphasis of this book has been placed on failure analysis investigations. Each case must be developed in a logical manner—large-scale

(macroscopic) features are initially investigated, then the microscopic features of the materials involved. Test specimen or samples of spacecraft hardware must be meticulously prepared, then examined using both light and electron microscopy. It is amazing how these techniques have evolved and how the recording of images has progressed. The author and his metallurgist contemporaries may well remember early student days when contributions to reports were exquisitely detailed hand drawn micrographs or images captured on photographic plates. The digital revolution has now enabled all levels of detail to be recorded using super-resolution microscopes and the future seems to be heading towards 3-dimensional microscopy.

In this book I have endeavoured to achieve a reasonable balance between general background knowledge and in-depth technical information. An elementary understanding of metals and materials on the part of the reader is assumed. I have deliberately excluded a comprehensive account of the techniques employed in modern materials laboratories (unless specifically related to unusual space material test methods). Many texts are available and cited in the Reference section. The Appendices have been extended and include many Tables related to: spacecraft materials' properties; alloy comparisons as they may be procured in different countries; a simplified M&P management guideline for universities; and, examples of Declared Materials and Processes Lists.

The space industry is a key sector in driving economic growth and creating new jobs. By 2030, the global space economy is predicted to be worth £400 billion per annum. At the time of writing, the European space manufacturing industry alone has an unprecedented overall turnover at £6 billion and a total direct employment of 38,000 persons. New spaceports will be established and spaceplanes are most likely to be the next generations' means for transporting commercial and scientific payloads into orbit. Many future spacecraft engineers, space scientist and technologists, all specialists in their own fields, may be aghast that some fundamental, 'old-hat' information is contained in this book. But it is the lessons-learnt scenarios that have brought us to where we are today. The industry is expanding and new employees need to learn from our past mistakes and, at least, understand why certain design rules exist.

The wide acceptance of the previous book has been most welcome, and I hope the new changes and additions will also find approval by my colleagues in the space industry and others in the wider engineering community.

Bosham, West Sussex  
December 2015

Barrie D. Dunn



---

## Acknowledgments

This book has been brought about by the blending of various published research and investigation projects that I have undertaken as a metallurgist for the European Space Agency, from some written works of others and from personal friends. I am especially grateful to the late Dr. Jacques Dauphin my former Division Head at ESA who gave the encouragement to undertake the writing of the earlier book. He was a native of the French province of Lorraine, where the motto is ‘Qui s’y frotte s’y pique’ which loosely translates to ‘gather thistles, expect prickles’—quite an apt maxim for those of us who have been involved with failure investigations. I also acknowledge the help received from my former ESA colleagues: Dr. Ton de Rooij, Jack Bosma, Guy Ramusat, Adrian Graham, David Collins and David Adams. Special thanks are also given to Dr. Ernst Semerad, Dr. A. Merstallinger, Grazyna Mozdzen and Markus Fink of the Aerospace and Advanced Composites GmbH (formally ARC), Wr. Neustadt, Austria, with whom I have had many years of professional collaboration. As previously stated, there has been a marked progress in this field of materials technology, resulting in significantly more citations to references in this Edition, but even so, the bibliographic information certainly is not complete. Where I have forgotten to cite a reference or credit an image I hope the author will forgive my oversight.

I am also grateful to ESA and NASA for some of the illustrations used in the book. It should be noted that the opinions expressed in this book are those of the author and do not necessarily reflect the policy of the European Space Agency.

Let me add a special note of thanks to my late wife, Hanneke, my son, Martin, and my daughter Harriet, for their patience through the spare-time hours that went into the making of the previous Edition. Also, to Anne for her unswerving support and help editing this present book. Stephen Hulcroft’s assistance at BlueFish Computer Services, Chichester is appreciated. I also wish to thank Clive Horwood, and the staff at Springer Praxis Books in Germany (Ms. Janet Sterritt) and India (Mr. Antony Raj Joseph and Ms. Sivajothi Ganesarathinam), for their assistance during the publication of this book.

The author would like to thank all his colleagues and friends at the following organisations who kindly supplied new information, reference material and photographs:

Torbjörn Lindblom, Celsius Materialteknik, Karlskoga, Sweden.

Dr. Michael Osterman, The Centre for Advanced Life Cycle (CALCE), University of Maryland, MD, USA.

S. Clément, Centre National d’Etudes Spatiales, Toulouse, France.

Dr. H. Boving, Centre Suisse d’Electronique et de Microtechnique SA, Neuchâtel, Switzerland.

H. Papenberg, DASA-ERNO Raumfahrttechnik GmbH (now Airbus Industries), Bremen, Germany.

D. Bagley, ERA Technology, Leatherhead, UK.

Dr. A. Feest, The Harwell Laboratory, Metals Technology Centre, Harwell, UK.

W. Feuring, Heraeus GmbH, Hanau, Germany.

Massimo Bonacci, High Technology Center (HTC), Foligno, Italy.

Poul Juul, Hytek, Aalborg, Denmark.  
Messrs G. Kudielka and W. Maier, IFE, Oberpfaffenhofen, Germany.  
Luca Moliterni and Gianluca Parodi, Italian Institute of Welding (IIS), Genoa, Italy.  
Norio Nemoto, Japan Aerospace Exploration Agency (JAXA), Tsukuba, Japan.  
Dr. Suman Shrestha, Keronite International Ltd., Haverhill, UK.  
P. Fletcher, Airbus (formally MMS-UK), Portsmouth, UK.  
Dr. Christopher Hunt, Martin Wickham and Ling Zou, The National Physics Laboratory, Teddington, UK.  
Dr. David Bernard, Nordson DAGE, Aylesbury, UK.  
Jo Wilson and Bob Hussey, RJ Technical Consultants, Juicq, France.  
Messrs Jörgen Svensson, U. Berg and Hans Ollfors, RUAG (formally Saab Ericsson Space), Gothenburg, Sweden.  
M.P. Hayes, The Spring Research and Manufacturers' Association, Sheffield, UK.  
Ian Turner, Cathy Barnes and Malcolm Snowdon, Spur Electron Ltd., Havant, UK.  
Dr. R. Eckert, Standard Elektrik Lorenz, Stuttgart, Germany.  
Dr. P. von Rosenstiel, Stichting Geavanceerde Metaalkunde, Hengelo, The Netherlands.  
Luca Soli and Ulisse Di Marcantonio, Thales Alenia Space Italia, Milan, Italy.  
Dr. J.M. Motz, Thyssen Guss AG, Mülheim a.d. Ruhr, Germany.  
Stephen Kyle-Henney, TISICS Ltd., Farnborough, UK  
Bill Strachan and Dr. Asa Barber, The University of Portsmouth, Portsmouth, UK.  
K. Ring, Zentrum für Verbindungs Technik, Gilching, Germany.  
Robert Wm. Cooke, NASA—Johnson Space Center, Houston, TX, USA  
Pablo D. Torres, NASA—Marshall Space Flight Center, Huntsville, AL, USA  
Dr. Fabiola Brusciotti, Tecnia, San Sebastian, Spain

---

# Contents

<b>1</b>	<b>Introduction.</b>	<b>1</b>
<b>2</b>	<b>Requirements for Spacecraft Materials</b>	<b>7</b>
2.1	General Background	7
2.2	Considerations for Materials and Processes	10
2.2.1	General Considerations During the Selection of Materials and Processes	10
2.2.2	Some Futuristic Ideas	11
2.2.3	Some Basic Considerations Regarding Corrosion Prevention	17
2.2.4	Space Project's Phases and Management Events	20
2.3	The Effect of a Space Environment	22
2.4	Materials for Space Launch Vehicles	28
2.5	Non-metallic Materials	38
2.5.1	General	38
2.5.2	Classes of Non-metallic Materials	42
2.5.3	Novel Non-metallics	43
2.6	The Potential for Welding and Joining in a Space Environment	49
2.6.1	Background Considerations	49
2.6.2	Potential Joining and Cutting Processes	50
2.6.3	Expectations	53
<b>3</b>	<b>The Integration of 'Materials' into Product Assurance Schemes</b>	<b>55</b>
3.1	General Product Assurance and the Role of Materials	55
3.1.1	Product Assurance Management	55
3.1.2	Quality Assurance	55
3.1.3	Reliability and Safety	57
3.1.4	Materials and Processes	59
3.1.5	Component Part Selection, and Procurement	61
3.1.6	Control of Ground-Handling Facilities	63
3.2	The Materials Laboratory	66
3.2.1	Major Objectives of Laboratory	66
3.2.2	Facilities and Instrumentation	67
3.2.3	The Use of New Laboratory Techniques for NDT	85
3.2.4	Organic Chemistry and Environmental Test Laboratories	98
3.3	Preparation of Materials and Metallographic Evidence	100
3.3.1	The Metallographer	100
3.3.2	Laboratory Records and Reports	101
3.3.3	Report of Materials Data to Spacecraft Projects	101
3.3.4	Training of Materials Engineers and Laboratory Staff	103
3.3.5	Ethical Issues	104

3.4	The Future for Materials Failure Investigations. . . . .	104
3.4.1	The Larger Company . . . . .	104
3.4.2	The Smaller Company. . . . .	105
3.4.3	Product Liability. . . . .	105
3.5	'Greener' Spacecraft. . . . .	105
3.6	The Potential for Recycling Electronic Waste. . . . .	111
3.6.1	General . . . . .	111
3.6.2	Elemental Distribution for Spacecraft Electronic Box . . . . .	111
<b>4</b>	<b>Spacecraft Manufacturing—Failure Prevention and the Application of Material Analysis and Metallography . . . . .</b>	<b>115</b>
4.1	Sources of Failure . . . . .	115
4.2	Drawings and Workmanship . . . . .	115
4.2.1	Design and Manufacturing Drawings. . . . .	115
4.2.2	Workmanship Standards . . . . .	116
4.3	Mechanical Damage Revealed by Microstructure . . . . .	122
4.4	Hydrogen Embrittlement . . . . .	122
4.4.1	Interaction of Metal with Hydrogen . . . . .	122
4.4.2	Hydrogen Embrittlement of Spring Steel . . . . .	123
4.4.3	Blistering of Plated Aluminium Alloy . . . . .	124
4.4.4	Examination for Titanium Hydride Precipitates. . . . .	125
4.4.5	Embrittlement of Copper . . . . .	127
4.4.6	Future Developments . . . . .	128
4.5	General Corrosion Problems . . . . .	128
4.5.1	Bimetallic Corrosion-Related Failures . . . . .	128
4.5.2	Corrosion Resistance of Anodic and Chemical Conversion Coatings on Al 2219 Alloy . . . . .	132
4.5.3	Evaluation of Alodine Finishes on Common Spacecraft Aluminium Alloys . . . . .	134
4.5.4	Cleaning, Passivation, and Plating of Spacecraft Steels . . . . .	137
4.5.5	Launch Site Exposure and Corrosion. . . . .	138
4.6	Stress-Corrosion Resistance of Metals. . . . .	139
4.6.1	Stress-Corrosion Cracking . . . . .	139
4.6.2	SCC Evaluation . . . . .	140
4.6.3	The Properties of Spring Materials . . . . .	144
4.6.4	Bearing Materials . . . . .	148
4.7	Control of Printed Circuit Boards. . . . .	148
4.7.1	Chemical Composition of Tin-Lead from Microstructure . . . . .	148
4.7.2	Grainy Solder Coverage on PCBs and the Effects of Rework. . . . .	150
4.7.3	Evaluation of Multilayer Board Internal Connections. . . . .	155
4.7.4	Flexible Circuits. . . . .	159
4.7.5	Hot-Air-Levelled Circuit Boards. . . . .	160
4.7.6	Solder Assembly of Component Packages onto Multilayer Boards with High Heat Capacity . . . . .	161
4.8	Control of Composite Materials . . . . .	161
4.8.1	Metal–Matrix Composites for Space Structures. . . . .	161
4.8.2	Composite Contact Devices . . . . .	164
4.8.3	Fibre-Reinforced Plastic Composites . . . . .	166
4.8.4	Fibre-Reinforced Glass Ceramics . . . . .	170
4.8.5	Carbon–Carbon Composites. . . . .	170
4.8.6	Metal Matrix Composites for Spacecraft Pressure Vessels . . . . .	172

4.9	Control of Capillary Screens . . . . .	172
4.10	Examination of Electroless Nickel Deposits . . . . .	173
4.10.1	Microcracked Electroless Nickel . . . . .	173
4.10.2	Electroless Nickel Plating of Aluminium Electronic Housings . . . . .	175
4.11	Control of Electroforming Processes . . . . .	176
4.12	Dip Brazing of Aluminium Alloys . . . . .	179
4.13	Considerations for the Assembly of Subsystems by Welding . . . . .	181
4.13.1	General Welding Methods and Controls . . . . .	181
4.13.2	Electron Beam Welding . . . . .	184
4.13.3	Laser Beam Welding . . . . .	185
4.13.4	Explosive Welding . . . . .	186
4.13.5	Welding of Aluminium–Lithium Alloys . . . . .	187
4.13.6	Welding of Thermoplastics for Space Applications . . . . .	188
4.14	Control of Power System Weldments . . . . .	189
4.14.1	General . . . . .	189
4.14.2	Welded Solar Arrays . . . . .	189
4.14.3	Suitability of Welded Battery Cells . . . . .	193
4.15	Problems Associated with Residual Stresses in Weldments . . . . .	195
4.16	Electromagnetic Emission from TIG Welding Equipment . . . . .	195
4.17	Titanium Aluminides for High-Temperature Applications . . . . .	196
4.18	Shape-Memory Alloys for Spacecraft Devices . . . . .	197
4.19	Foamed Aluminium for Damping Purposes . . . . .	202
4.20	Superplastic Forming and Diffusion Bonding of Metals . . . . .	203
4.20.1	Forming of Propellant Tanks . . . . .	203
4.20.2	Diffusion Bonding . . . . .	206
4.20.3	Superplastic Forming and Diffusion Bonding in One Operation . . . . .	206
4.21	Cleaning of Mechanical Parts . . . . .	207
4.21.1	General Background . . . . .	207
4.21.2	Metallic Surfaces . . . . .	209
4.21.3	Cleaning of Individual Parts . . . . .	210
4.21.4	Cleaning of Metallurgically Joined Assemblies . . . . .	213
4.21.5	Maintenance of Cleanliness . . . . .	216
4.21.6	Cleaning of Silicone Contamination . . . . .	219
4.22	Novel Thermal Management Materials . . . . .	220
4.23	Cold Sprayed Coatings . . . . .	223
4.24	Advanced Plasma Electrolytic Oxidation Treatment for Aluminium, Magnesium and Titanium Alloys . . . . .	224
4.24.1	General Process . . . . .	224
4.24.2	Characteristics of PEO Coatings . . . . .	225
4.24.3	Applications . . . . .	229
4.25	Joining by “Friction Stir” . . . . .	231
4.25.1	Friction Stir Welding . . . . .	231
4.25.2	Friction Stud Welding . . . . .	234
4.26	Selective Brush Electroplating . . . . .	234
4.27	Control of Coatings and Bonded Items by Tape Testing . . . . .	237
4.28	The Application of EB Welding Machine for Reflow Brazing . . . . .	239

<b>5</b>	<b>Metallography Applied to Spacecraft Test Failures . . . . .</b>	<b>247</b>
5.1	Application of Electron Microscope . . . . .	247
5.1.1	SEM Examination of Fracture Surfaces . . . . .	247
5.1.2	TEM Examination of Metallic Failures . . . . .	250
5.2	Fasteners . . . . .	251
5.2.1	Spacecraft Fasteners . . . . .	251
5.2.2	Fastener Failure Due to Forging Defect . . . . .	254
5.2.3	Laps and Surface Irregularities in Threads . . . . .	255
5.2.4	Hydrogen Embrittlement of Steel Fasteners . . . . .	255
5.2.5	Embrittlement of Titanium Alloys . . . . .	255
5.2.6	Galvanic Corrosion of Fasteners . . . . .	257
5.2.7	Contamination and Organic Fastener Lubrication Systems . . . . .	257
5.2.8	Metallic Particle Generation . . . . .	258
5.2.9	Quality Assurance Controls for Fasteners . . . . .	261
5.3	Thermal History from Microstructure . . . . .	262
5.4	Effect of Inclusions Within the Microstructure of Explosively Deformed Material . . . . .	264
5.5	Degradation of Passive Thermal Control Systems . . . . .	266
5.5.1	General Background . . . . .	266
5.5.2	Low-Emissivity Surfaces . . . . .	268
5.5.3	High-Absorption Surfaces . . . . .	269
5.5.4	Rigid Optical Solar Reflectors . . . . .	270
5.5.5	Flexible Second Surface Mirrors . . . . .	271
5.6	Sublimation of Metals . . . . .	272
5.6.1	General . . . . .	272
5.6.2	Sublimation of and Condensation of Cadmium and Zinc . . . . .	274
5.6.3	Heater Sublimation Problem Associated with Thruster Motor . . . . .	276
5.6.4	Sublimation of Klystron Cathode-Heaters . . . . .	276
5.6.5	Sublimation of Rhenium . . . . .	278
5.7	Beryllium for Spacecraft Applications . . . . .	280
5.7.1	General . . . . .	280
5.7.2	Health and Safety . . . . .	281
5.7.3	Integrity of Machined Beryllium . . . . .	283
5.7.4	Thermal Cycling on Work-Hardened Beryllium . . . . .	284
5.7.5	General Etching Solutions for Beryllium . . . . .	285
5.7.6	Investigation of Microcracked Thin-Foil Detector Windows . . . . .	286
5.7.7	Aluminium-Beryllium Alloys . . . . .	288
5.8	Deactivation of Catalyst Particles for Hydrazine Decomposition . . . . .	288
5.8.1	Testing Procedure . . . . .	288
5.8.2	Material Investigation . . . . .	288
5.8.3	Mechanism of Particle Deactivation . . . . .	290
5.9	Cathode Emitter Degradation . . . . .	291
5.10	Investigation of a Failed Spacecraft Antenna . . . . .	293
5.11	The Wear of Ball Bearings . . . . .	296
5.12	Cold Welding of Mechanisms . . . . .	304
5.12.1	General . . . . .	304
5.12.2	Cold Welding Due to Cyclic, Impact Loading . . . . .	306
5.12.3	Cold-Welding Due to Fretting . . . . .	307
5.13	Defective Black-Anodized Electrical Connector . . . . .	308
5.14	Contaminant Particles—Identification of Their Sources . . . . .	309

5.15	Silicone Contamination . . . . .	310
5.15.1	General . . . . .	310
5.15.2	Contamination of Black-Anodized Finish. . . . .	311
5.15.3	Contamination of Invar Moulding Tool . . . . .	312
5.15.4	Removal of Silicone Polymers . . . . .	314
5.15.5	Contamination of Aluminium Tubes for Vacuum Pinch-Offs . . .	317
5.16	Magnetic Problems . . . . .	317
5.17	Thermal Stress-Induced Dimensional Changes . . . . .	319
5.17.1	General Problems . . . . .	319
5.17.2	Stress-Relaxation by Thermal Gradients. . . . .	319
5.17.3	Thermally Induced Vibrations . . . . .	321
5.18	Defects in Titanium Piece-Parts . . . . .	323
5.18.1	General . . . . .	323
5.18.2	Alpha-Case Embrittlement . . . . .	323
5.18.3	Titanium Hydride Embrittlement. . . . .	324
5.19	Leaking Water Tank on Launcher. . . . .	325
5.20	Compatibility of Liquid and Solid Propellants with Components and Subsystems . . . . .	326
<b>6</b>	<b>Failure Analysis of Electrical Interconnections and Recommended Processes . . . . .</b>	<b>329</b>
6.1	Material Problems . . . . .	329
6.2	Welded Lead Wire Interconnections . . . . .	329
6.3	'Purple Plague' . . . . .	332
6.4	Mechanical Electrical Connections . . . . .	337
6.4.1	General . . . . .	337
6.4.2	Wire-Wrapped Connections . . . . .	337
6.4.3	Crimped Joints . . . . .	339
6.5	Soldered Interconnections . . . . .	340
6.5.1	Introduction to Soldering . . . . .	340
6.5.2	Inspection of Soldered Joints . . . . .	341
6.5.3	The Effect of Thermal Fatigue on Solder-Assembled Leaded Components . . . . .	344
6.5.4	Effect of Thermal Fatigue on Leadless Components . . . . .	351
6.5.5	The Effect of Thermal Fatigue on Semi-rigid Cable Connections . . . . .	353
6.6	Problems Associated with Coatings for Soldering Applications . . . . .	357
6.6.1	The Need for Coatings . . . . .	357
6.6.2	Surfaces that Can Be 'Soldered To' . . . . .	357
6.6.3	Surfaces that Can Be 'Soldered Through' . . . . .	359
6.7	The Use of Indium Solder Alloys. . . . .	363
6.8	Wires and Cables . . . . .	369
6.8.1	Selection of Plated Finish on Copper Conductors . . . . .	369
6.8.2	Effect of Ageing on the Solderability of Tin-Plated and Silver-Plated Wires . . . . .	371
6.8.3	'Red Plague' Corrosion of Silver-Plated Copper, and Plagues on Other Plated Stranded Wires . . . . .	375
6.8.4	Manganin Wire . . . . .	379
6.8.5	High-Voltage Wires, Cables, and Connections . . . . .	380
6.8.6	Cold Welding of Stranded Wires and Cables . . . . .	380

6.9	Problems Associated with Soldering Fluxes . . . . .	380
6.9.1	Purpose of a Flux . . . . .	380
6.9.2	Heat-Shrinkable Sleeves Containing Solder Preforms . . . . .	381
6.9.3	Stress Corrosion of Component Lead Material . . . . .	383
6.9.4	Flux-Corrosion of Silver-Plated Stranded Wires . . . . .	383
6.9.5	Selection of a Soldering Flux or a Solderable Finish . . . . .	386
6.9.6	Control of Galvanic Corrosion . . . . .	389
6.9.7	Cleaning of Flux-Contaminated Surfaces . . . . .	389
6.9.8	Flux Residues, Their Ingress into Top-Coat of PCB Surfaces, and Bake Out After Cleaning . . . . .	391
6.9.9	Conductive Anodic Filament (CAF) Formation and Particulate Contamination . . . . .	394
6.9.10	Potential Health Hazards in the Electronic Assembly Area . . . . .	398
6.10	Problems Associated with Brazing . . . . .	399
6.10.1	Design Considerations . . . . .	399
6.10.2	Brazeability of Materials and Braze Alloy Compositions . . . . .	400
6.10.3	Brazing Fluxes and Their Removal . . . . .	403
6.10.4	Atmospheres for Brazing . . . . .	404
6.10.5	Safety Precautions . . . . .	405
6.10.6	Produce Assurance Applied to Brazing Operations . . . . .	405
6.10.7	Inspection Criteria for Brazed Aluminium Alloy Waveguide-to-Flange Joints . . . . .	406
6.11	Diffusion Soldering/Brazing . . . . .	408
6.12	Effects of Rework and Repair on Soldered Interconnections . . . . .	408
6.12.1	General . . . . .	408
6.12.2	Cosmetics of Solder Fillets . . . . .	410
6.12.3	Effect of Rework Electronic Components . . . . .	410
6.12.4	Effect of Rework on Plated-Through Holes . . . . .	410
6.12.5	Effect of Rework on Composition of Joint . . . . .	412
6.12.6	Recuperation of Unsolderable PCBs and Component Leads . . . . .	413
6.13	Electrical Conductive Adhesives . . . . .	413
6.14	Training and Certification . . . . .	415
6.14.1	General . . . . .	415
6.14.2	Certification for Electronic Assembly Techniques . . . . .	417
6.14.3	Understanding Process-Induced Failures and the Importance of Workshops . . . . .	418
6.15	Verification of Surface-Mount Technology and Prevalent Failure Mechanisms . . . . .	419
6.15.1	Verification Testing . . . . .	419
6.15.2	Failure Under Mechanical Overloading . . . . .	422
6.15.3	Failures Due to Board Flatness Problems . . . . .	422
6.15.4	Failure Due to Co-planarity Problems . . . . .	423
6.15.5	Solder Joint Failure Due to Thermal Mismatch Between SMD and Substrate . . . . .	425
6.15.6	Conductor Track Failure Due to Thermal Mismatch . . . . .	428
6.15.7	Failure of RF Cables Connected by SMT . . . . .	428
6.15.8	SMT Solder Joint Failure Due to Conformal Coatings . . . . .	428
6.15.9	SMT Problems Related to Flux and White Residues . . . . .	432
6.15.10	Area Grid Array (AGA) Packaging . . . . .	434



6.15.11	High Voltage Interconnections and Influence of Geometry (Workmanship) on Corona Discharge . . . . .	442
6.15.12	Tin Pest. . . . .	448
6.15.13	Mechanical and Electrical Properties of Electronic Materials at Temperatures Down to 4.2 K . . . . .	451
<b>7</b>	<b>Whisker Growths . . . . .</b>	<b>461</b>
7.1	The Problem of Whisker Growth . . . . .	461
7.2	Analysis of Failures Due to Whisker Growth . . . . .	462
7.2.1	Molybdenum Whiskers on Metallized Miniature Circuits . . . . .	462
7.2.2	Tungsten Whisker Growth Within Travelling Wave Tubes . . . . .	466
7.2.3	Metal Oxide Whisker Precipitation in Glass Seals . . . . .	466
7.2.4	Integrated Circuit Failure Modes Due to Electromigration—Aluminium Whisker Growth and Solder Joint Voiding . . . . .	468
7.3	Tin Whisker Growths . . . . .	472
7.3.1	Tin Whisker Growth on a Plated Steel Housing . . . . .	472
7.3.2	Tin Whisker Growth on PCB and Other Electronic Materials During Thermal Cycling . . . . .	474
7.3.3	Tin Whisker Growth on Crimp Termination Devices . . . . .	479
7.3.4	The Nucleation, Growth and Mechanism of Growth of Tin Whiskers—Results from a C-Ring Test Programme . . . . .	481
7.3.5	Some Properties of Tin Whiskers . . . . .	485
7.4	Precautions to Avoid General Whisker Growths . . . . .	491
7.5	The Creation of Lead-Free Control Plans . . . . .	494
7.5.1	General . . . . .	494
7.5.2	Methods for Reprocessing Pure Tin Terminations . . . . .	495
7.5.3	Mitigation Approaches . . . . .	498
<b>8</b>	<b>Assessment of Post-flight Materials . . . . .</b>	<b>501</b>
8.1	General . . . . .	501
8.1.1	Hardware Return from Space . . . . .	501
8.1.2	Raw Materials from the Moon . . . . .	501
8.1.3	Recent Investigations Using Retrieved Materials . . . . .	503
8.2	Space Environmental Effects from Vacuum and Radiation . . . . .	503
8.2.1	Organic Materials and Lubricants . . . . .	503
8.2.2	Radiation Effects . . . . .	507
8.2.3	Effects of Vacuum on Metals . . . . .	508
8.3	Temperature Cycling . . . . .	509
8.4	Micrometeoroids and Debris . . . . .	509
8.4.1	General . . . . .	509
8.4.2	Debris Emanating from Catalytic Bed Thruster Motors . . . . .	512
8.4.3	Returned Hardware . . . . .	514
8.4.4	Protection Shields . . . . .	515
8.5	Effect of Atomic Oxygen on Materials . . . . .	517
8.6	Decelerators and Heat Shield Materials . . . . .	524
8.6.1	General Examples . . . . .	524
8.6.2	Beryllium as a Heat Shield . . . . .	528
8.6.3	Alternative Heat Shield Materials . . . . .	531
8.6.4	High-Temperature Fasteners . . . . .	533

8.7	Manned Compartments . . . . .	535
8.7.1	General Conditions . . . . .	535
8.7.2	Solder Assembly Defects . . . . .	538
8.7.3	Inspection of Spacelab Post-flight Hardware. . . . .	542
<b>Appendix 1: Coefficient of (Linear) Thermal Expansion for Selected Materials (COE or CTE) . . . . .</b>		<b>557</b>
<b>Appendix 2: Properties of Printed Circuit Laminates . . . . .</b>		<b>559</b>
<b>Appendix 3: Reagents for Microetching Metals and Alloys . . . . .</b>		<b>561</b>
<b>Appendix 4: Conversion Table for Mechanical Properties . . . . .</b>		<b>565</b>
<b>Appendix 5: Aluminium Alloy Temper Designations . . . . .</b>		<b>567</b>
<b>Appendix 6: Metal Alloy Comparison Tables . . . . .</b>		<b>571</b>
<b>Appendix 7: Variation of Standard Free Energy of Formation of Oxides with Temperature . . . . .</b>		<b>613</b>
<b>Appendix 8: Simplified Procedure for the Management of Materials, Processes and Mechanical Parts—Possible Guidelines for a Cubesat or Small University Spacecraft . . . . .</b>		<b>615</b>
<b>Appendix 9: Materials and Processes Standards Related to Space (Released by ECSS, JAXA and NASA) as of 2015 . . . . .</b>		<b>619</b>
<b>Appendix 10: Examples of Declared Process Lists (DPL). . . . .</b>		<b>621</b>
<b>Appendix 11: Examples of Declared Materials Lists (DMLs) . . . . .</b>		<b>625</b>
<b>Glossary . . . . .</b>		<b>629</b>
<b>References. . . . .</b>		<b>639</b>
<b>Index . . . . .</b>		<b>655</b>